PERMEABILITY VARIATION WITH CO$_2$ INJECTION IN COALGAS RESERVOIRS AND ITS IMPACT ON METHANE PRODUCTION

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ABSTRACT

Carbon sequestration in coalgas reservoirs as a technique to combat atmospheric CO$_2$, while simultaneously enhancing the recovery of gas, is a viable option in the immediate future. However, injected CO$_2$ in deep coals not only displaces additional methane while getting adsorbed, but also results in swelling of the solid coal matrix associated with adsorption. This, in turn, reduces the cleat aperture, and hence, the coal permeability. A significant reduction in permeability can hinder the flow of CO$_2$/CH$_4$ in the reservoir making this option of CO$_2$ sequestration economically infeasible. It is, therefore, important to study the flow characteristics of coal resulting from gas injection in order to accurately predict the amount of additional methane recovery, and determine the viability of using deep coal as CO$_2$ repositories.

As a part of a study to determine the impact of permeability reduction resulting from CO$_2$ injection, an experimental study was carried out to measure the volumetric strain induced in coal matrix with sorption of gases. First, the matrix "shrinkage" with desorption and flow of methane was measured. This was followed by measuring the matrix "swelling" induced by injection of CO$_2$. Using the measured matrix volumetric strain, changes in coal permeability were estimated numerically. The variation in permeability was then entered in a commercial CBM simulator and its impact on long-term gas production was evaluated. Finally, methane recovery with injection of CO$_2$ after partial depletion, and the effect of matrix swelling was simulated. This paper describes the experimental work, results obtained to date, and the preliminary results of the simulation exercise.

INTRODUCTION

The adverse impact of increasing concentrations of carbon dioxide in atmosphere has propelled the need to find ways to control it. Although a significant amount of research is underway to study different ways of decreasing the amount of atmospheric CO$_2$, sequestration of CO$_2$ in coal seams is the primary available alternative, which is both feasible and practical in the immediate future [1, 2, 3]. Coal seams provide an excellent target for CO$_2$ sequestration due to the ability of coal to physically adsorb large volumes of CO$_2$, the ease of availability of deep coalbeds throughout the world, and their proximity to power plants which are considered to be the main source of CO$_2$ emissions [1, 2]. Also, a considerable amount of knowledge has been acquired, technology and models developed in the area of coalbed methane (CBM) recovery, all of which can be easily adapted to CO$_2$ flow and storage. Thus the concept of CO$_2$ sequestration, coupled with enhancement of coalbed methane recovery to serve as an incremental energy source, is considered to provide a good synergy for long-term benefits, one being environmental and the other economical. The revenues generated from the additional methane recovered can offset the cost of CO$_2$ sequestration, making this process economically feasible. Enhanced recovery can also make marginal coal properties, which are low in gas content, or those which have already undergone primary depletion, an attractive target for CO$_2$ sequestration and methane production.

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In order to predict the economic viability of the process, it is very important to study the behavior of coal when CO_2 is injected, and the impact of the resulting variation in the physical properties of coal on recovery of methane, flow of CO_2, and the sequestration potential.

It is well known that volume of solid coal changes with *ad/de* sorption of gases. This phenomenon is referred to as "matrix shrinkage" in CBM operations, and results in an increase in the permeability of coal due to widening of the fractures (cleats) [4, 5]. A number of studies conducted in the past have concluded that this is, in fact, the case and it has also been corroborated by field operations in the San Juan and Black Warrior Basins [1, 6

Likewise, there is "swelling" of coal matrix resulting from injection of sorbing gases [7, 8]. Although no studies have been conducted to date to investigate the effect of matrix swelling on coal properties, limited field observations and available data show a dramatic reduction in the permeability of coal as a result of CO_2 injection [2, 6]. Since this can have a significant influence on the injectivity of CO_2, the associated enhancement of methane production, and CO_2 sequestration potential, a complete understanding of the changes in coal properties is essential in order to predict the long-term impact of CO_2 sequestration on methane recovery.

This paper takes in to consideration the volumetric strain measurements induced in the coal matrix due to CO_2 injection, and estimates the impact of the resulting variation in permeability on the recovery of methane using reservoir simulation. Since the laboratory study was conducted using samples from the Illinois Basin, the entire analysis is based on either measured or realistic values of input parameters for the basin. Comet 3, a three-component, two-phase, black oil simulator with an ability to simulate enhanced recovery scenarios was used to estimate the impact on the short- and long- term production.

BACKGROUND

Field experience with CO_2 injection is limited to Allison Unit (operated by Burlington Resources) in the San Juan Basin, Upper Silesian Basin in Poland (RECOPOL PROJECT) [14], and Alberta Sedimentary Basin of Canada (by Alberta Research Council). Two projects, Coal Sequestration Project in Japan and China ECBM Project, have also been started recently. The RECOPOL and Alberta project are still in their development phase, although some preliminary assessment has been completed. Hence, Allison unit, the world's first CO_2-ECBM recovery pilot, is the only one for which significant field data is available. Consisting of 16 production wells and 4 CO_2 injection wells, CO_2 injection was started in 1995 and continued intermittently until 2001 [6]. Analysis of the results clearly demonstrated the potential of CO_2 sequestration in coalbeds along with the enhancement of methane recovery. There was an increase in ultimate methane production as well as the rate of recovery although the increase was well below that forecasted. The discrepancy was attributed to a significant permeability loss, estimated to be as high as 100 times, resulting in injectivity losses and demonstrating the adverse impact of CO_2 injection on project economics.

LABORATORY EXERCISE

The determination of coal matrix swelling as a result of CO_2 injection, and its subsequent effect on permeability, was the foundation of this analysis. The sorption induced volumetric strains were measured in the laboratory. Details of the investigation can be found in Zutshi and Harpalani [9]. The measured strains were used to calculate the changes in cleat porosity and permeability. Matrix shrinkage compressibility and matrix swelling factor [12] for CO_2 were also

calculated using laboratory measurements. The laboratory measured and derived values were then used as input parameters for the simulation exercise.

SIMULATION EXERCISE

A sample test reservoir with coalbed properties representative of Illinois region was developed for the simulation [Appendix 1]. Due to lack of any detailed study, not all properties of Illinois coal were known. For parameters not available, average values of properties of currently producing regions were used. Thus the sample test reservoir is not an accurate representation of the actual field conditions. A list of input parameters used is included in Tables 1 and 2.

In order to analyze the effects of CO_2 injection, a base case scenario of dual porosity, single permeability, and single component gas with two-phase gas-water system was considered. Coalbed properties were assumed isotropic and matrix shrinkage effect on permeability was taken into account. Grid blocks were constructed in Cartesian geometry with production wells placed in a five spot pattern. Methane recovery by the primary depletion method was first simulated. This was considered the base case for the rest of the analysis.

For CO_2 injection scenario, changes were made to the base case with two additional injection wells positioned on the sides of the grid block, as shown in Figure 1. After 1000 days of primary production, CO_2 was injected at a bottom-hole pressure of 1300 psi for the rest of the period simulated. Matrix swelling effect due to CO_2 injection was included in the simulation study. The results of CO_2 injection study were compared with the base case in order to analyze the impact of injection on reservoir properties, and also to determine the "enhancement" of methane recovery achieved, if any.

RESULTS AND DISCUSSIONS

Base Case – Figure 2 shows the methane and water production rates for an approximate period of 3000 days. The results of the simulation indicate that, during the first few days, there is a sharp increase in methane production rate. This increase is attributed to the production of free methane present in coal along with water. Secondly, the production of water increases the gas relative permeability of coal and, therefore, the flow of gas. After the initial surge, methane production rate falls rather sharply for a short period, and then gradually declines for the remaining period simulated. The first decline is the result of depletion of free methane present in the fractures, and this amount is usually small. Beyond this stage, the production is primarily due to the methane desorbing in the matrix and diffusing towards the cleat network, and the process of desorption starts only after a certain reduction in gas pressure. All of the methane produced beyond this point is desorbing methane. The process of desorption continues at a slow pace, resulting in a continuous but slow depletion. The reduction in production rate is also the result of increased effective stress.

CO_2 INJECTION – Figure 3 shows the methane production rate for a CO_2 injection (ECBM) scenario. Subsequent to CO_2 injection, 1000 days after methane production started, there is an increase in the production rate, clearly indicating the positive impact of CO_2 injection on methane recovery. Figure 3 shows that the rise in methane production rate is almost instantaneous with injection. Figure 4 shows the increase in the reservoir pressure, and this increase corresponds with the increase in methane production rate. This suggests that the injected CO_2 is getting adsorbed on coal as a result of increase in pressure, while the methane is being displaced resulting in

increased methane production rate. The increase in pressure also has a secondary effect that might be playing a significant role in increased production. The usual increase in effective stress associated with depletion, and the resulting permeability loss, is prevented. Regardless of the mechanism(s) involved, methane production rate continues to rise until CO_2 breakthrough occurs at approximately 1200 days after the commencement of injection, as shown in Figure 5. After breakthrough, the methane production rate declines rapidly (Figure 3). By then, coal is probably getting increasingly saturated with CO_2 with little methane left in the coal to desorb, diffuse and flow, and there is a corresponding decrease in the ability of coal to adsorb CO_2. The amount of injected CO_2 recovered at the producer wells starts increasing, and there is a rising trend of CO_2 production rate beyond this. This will probably continue until there is absolutely no additional adsorption of injected CO_2, i.e., CO_2 production rate would equal the rate of injection, at which point the reservoir would be fully saturated with CO_2. It can also be seen that, after a certain period of injection, injectivity of CO_2 decreases due to matrix swelling, resulting in a decline of CO_2 injection rate. This is probably coupled with the fact that the rate of additional CO_2 adsorption starts to slow down.

The simulation results were used to estimate the incremental methane recovery as a result of CO_2 injection by comparing the cumulative methane production with and without injection (base case versus the ECBM scenario), and this is shown in Figure 6 and Table 3. With CO_2 injection, there is an increase in methane recovery of over 130% compared to base case, or the primary depletion method, for the period simulated. This increase in recovery is primarily due to displacement of methane by CO_2. Another interesting observation is that the cumulative water production increases in the case of CO_2 injection by about 11%.

As a final step, the effect of matrix swelling was estimated. Figure 7 illustrates the impact of matrix swelling on methane recovery. It compares methane production rates for the two cases, one taking into account the matrix swelling effect, and the other ignoring it. It can be seen in Figure 8 that increase in methane recovery is higher in the latter case. In fact, matrix swelling is responsible for almost 36% reduction in methane recovery – for the period simulated.

Figure 9 illustrates the amount of CO_2 sequestered in the coal seam. After 2000 days of continuous CO_2 injection, little CO_2 is obtained at the producer wells. This is contrary to N_2 injection, where breakthrough is rather immediate. For the period simulated, the amount of CO_2 sequestered is 1.4 BCF. Finally, a comparison of Figures 3 and 8 shows that the amount of CO_2 sequestered is more than four times the additional methane produced.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this preliminary simulation study, the following conclusions are made:

- Permeability reduction resulting from CO_2 injection can compromise the project performance and economics by having a fairly significant adverse impact on incremental methane recovery and CO_2 injectivity. In fact, incremental recovery with CO_2 injection, beyond that estimated by primary recovery, depends on the swelling characteristics of coal.

- Although methane production rate and CO_2 breakthrough might not permit continued production of methane beyond a certain point, the potential to sequester CO_2 in coal is apparent even after that. Hence, economics apart, sequestration of CO_2 in coal, particularly depleted coalgas reservoirs, is enormous.

- The increase in methane production rate may be the result of displacement of methane as well as the absence of permeability loss usually resulting from increased effective stress.

- The reasons for the fall in CO_2 injectivity needs to be investigated further. Apart from matrix swelling, the decrease in injectivity can also be due to the relative permeability effects, which should be studied further.

- The phenomenon of bi-directional diffusion (CO_2- in, CH_4-out) in the coal matrix needs to be investigated. The occurrence of bi-directional diffusion in the coal matrix can affect the deliverability of methane.

- Further investigation of the time dependant nature of permeability reduction is essential. It can provide the basis for determining variations in methane production rate and CO_2 injectivity with time. Also, it will enable estimating the time lag between CO_2 injection and the beginning of its effect on methane recovery in the form of increased production rate.

- The current effort should be continued to study the permeability variation with flue gas injection using simulated flue gas with different proportions of CO_2 and N_2.

ACKNOWLEDGEMENT

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APPENDIX 1

Coalbed properties
Coal seam thickness: 9 ft
Depth of coal seam: 900 ft
Fracture permeability: 5 md
Porosity of natural fracture: 0.01
Coal compressibility: 800 x 10E-06/psi
Matrix shrinkage comp.: 2.07 x 10E-06/psi
Differential swelling factor (CO_2): 2.0

Reservoir Properties
Temperature: 75° F
Pressure: 525 psi
Water saturation: 0.9
Water viscosity: 0.73

Grid System
Rectangular: 11 x 11 x 1
X-dir length: 1100 feet
Y-dir length: 1100 feet
Z-dir length: 9 feet
Area: 250 acres

Operating Conditions:
Well locations:
Producer 1: (4, 4, 1)
Producer 2: (8, 4, 1)
Producer 3: (6, 6, 1)
Producer 4: (4, 8, 1)
Producer 5: (8, 8, 1)
Injector 1:   (6, 1, 1)
Injector 2:   (6, 1, 1)
CO_2 injection commencement -1000 days
Injection bottom-hole pressure: 1300 psi

Table 1: Langmuir Isotherm Table

	Methane	CO_2
Langmuir Pressure, psia	400	204.5
Langmuir Volume, scf/cuft	25.164	40.2

Table 2: Relative Permeability Table

Water Saturation	$\mathbf{k_{rw}}$	$\mathbf{k_{rg}}$
0.70	0.000	0.650
0.75	0.040	0.500
0.80	0.060	0.350
0.85	0.160	0.175
0.90	0.250	0.050
0.95	0.350	0.015
1.00	1.00	0.000

Table 3: Results of Simulation – 3000 Days

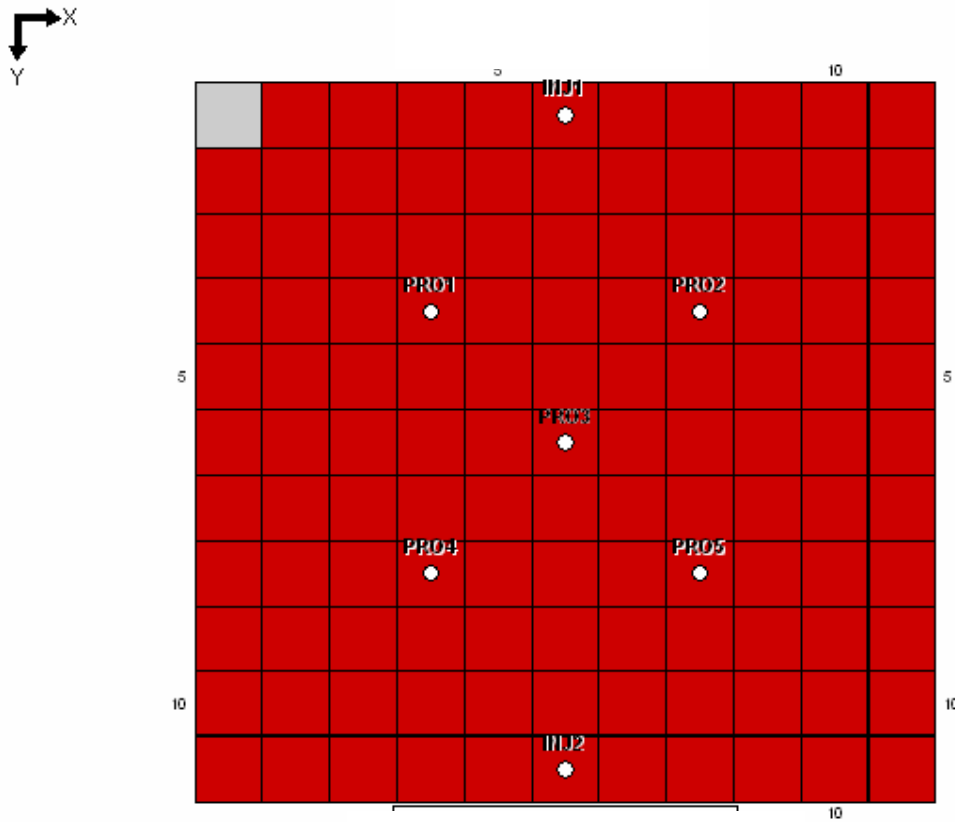|	**Base Case**	**CO_2 Injection**
Gas in Place, BCF	1.38	1.38
Cum. CH_4 Production, BCF	0.26	0.59
Cum. CO_2 Injection, BCF	–	1.47
Cum. CO_2 Production, BCF	–	0.07
Cum. Water Production, MBBLS	27	30

Figure1: Layout of wells in the hypothetical reservoir simulated.
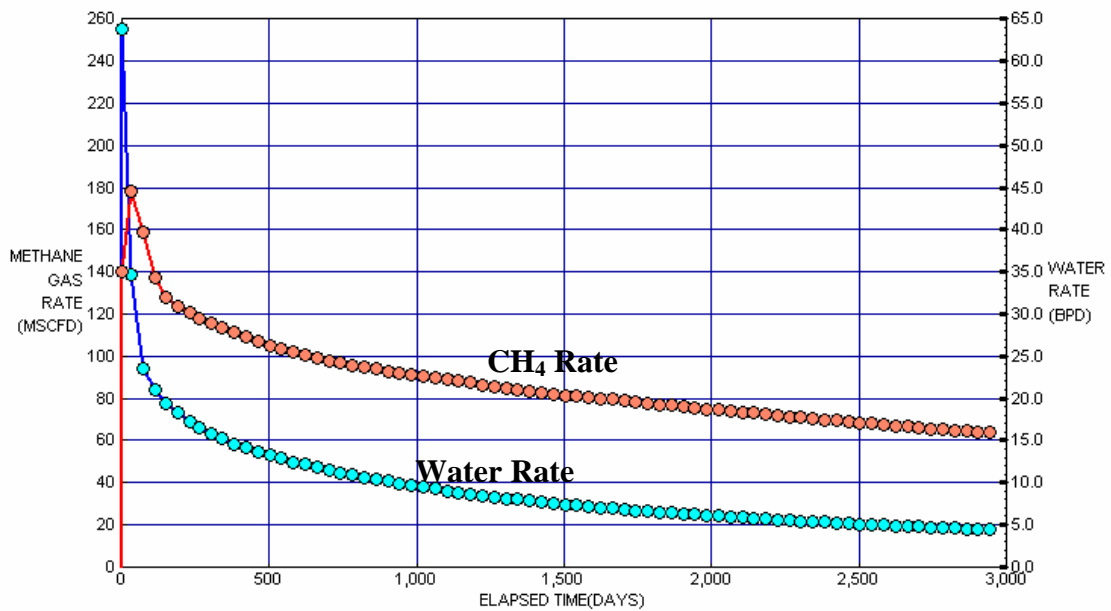

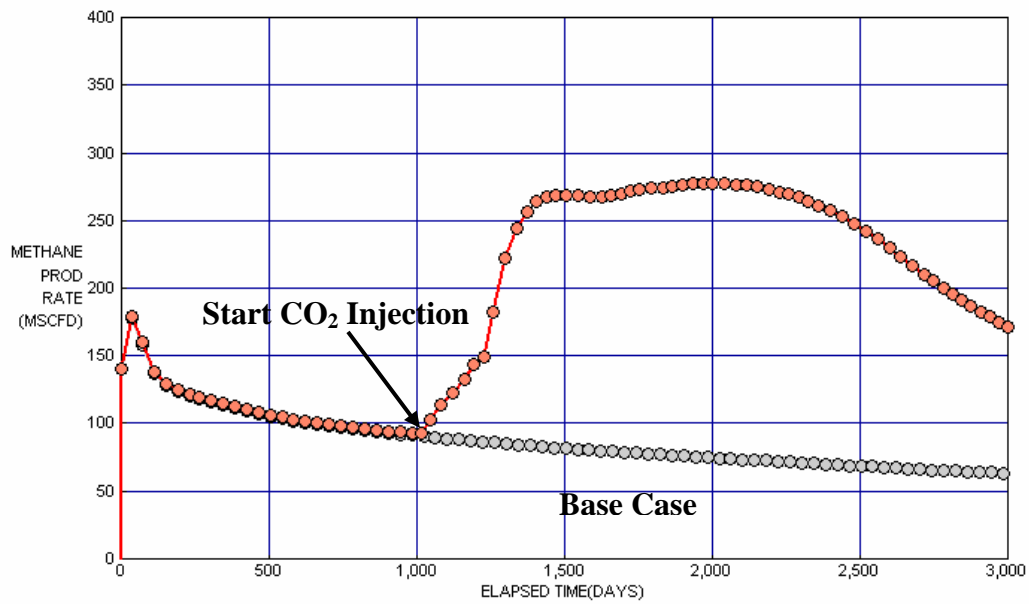Figure 2: Methane and water production rates in base case scenario.

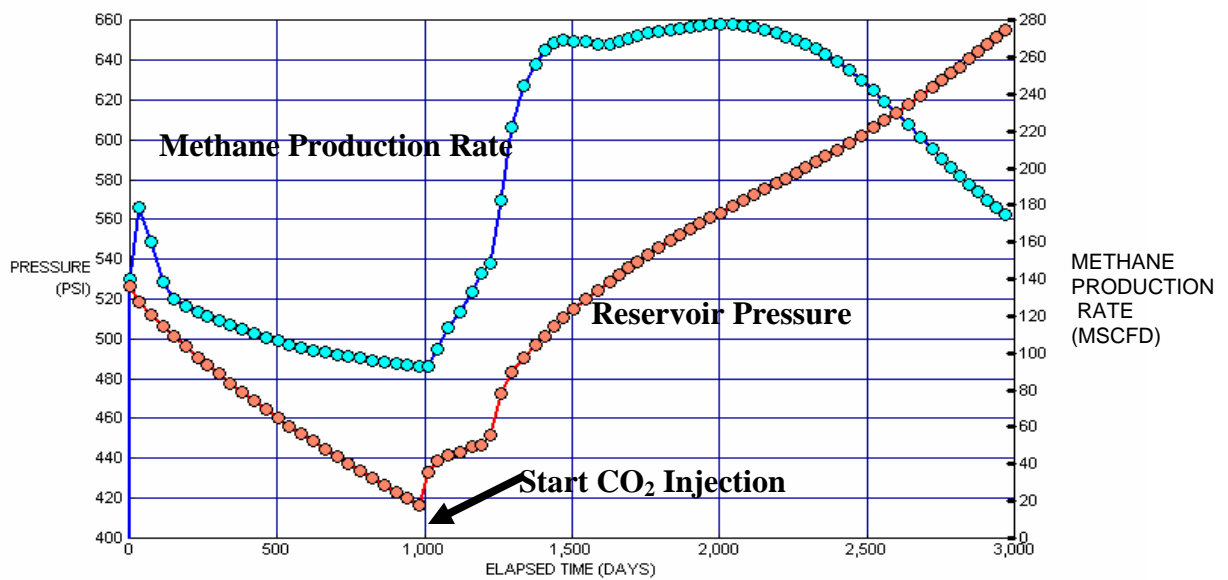Figure 3: Methane production rate with CO_2 injection.

Figure 4: Methane production rate and reservoir pressure for CO_2 injection case.
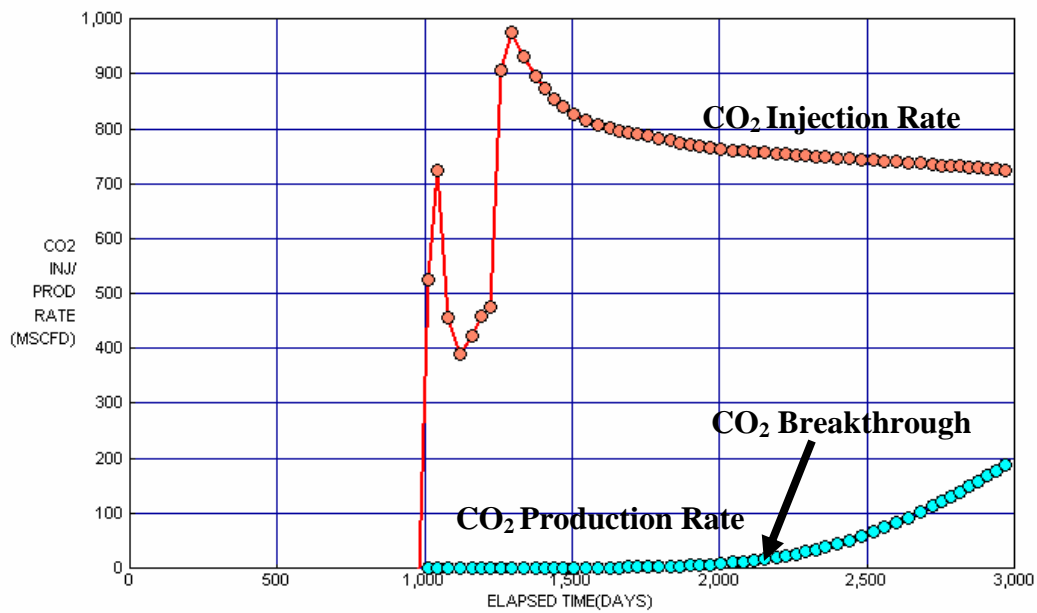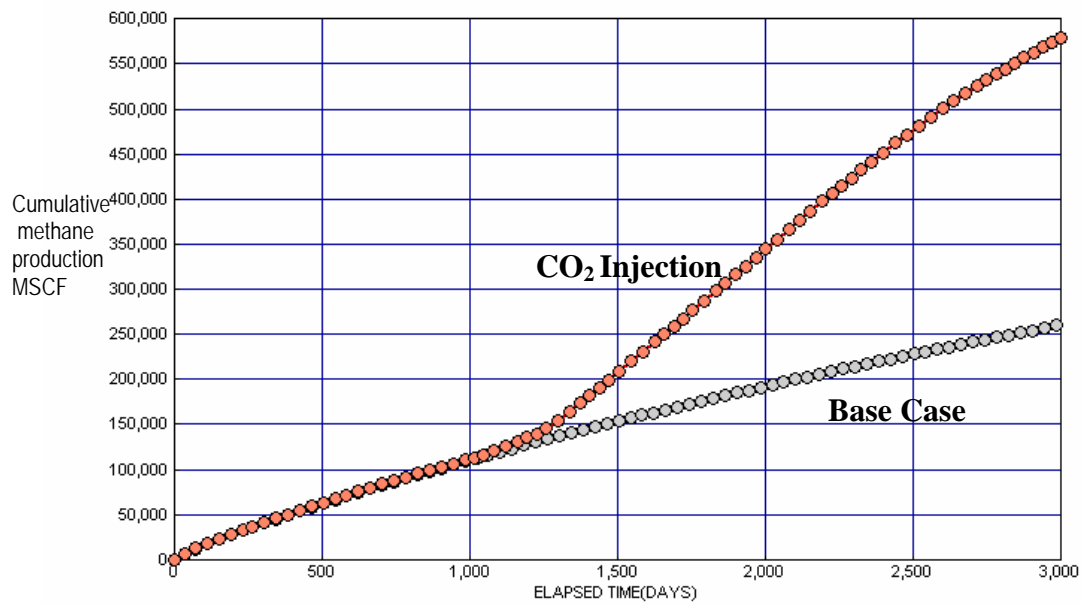
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Figure 5: CO_2 injection and production rates.

Figure 6: Cumulative methane produced with and without CO_2 injection.
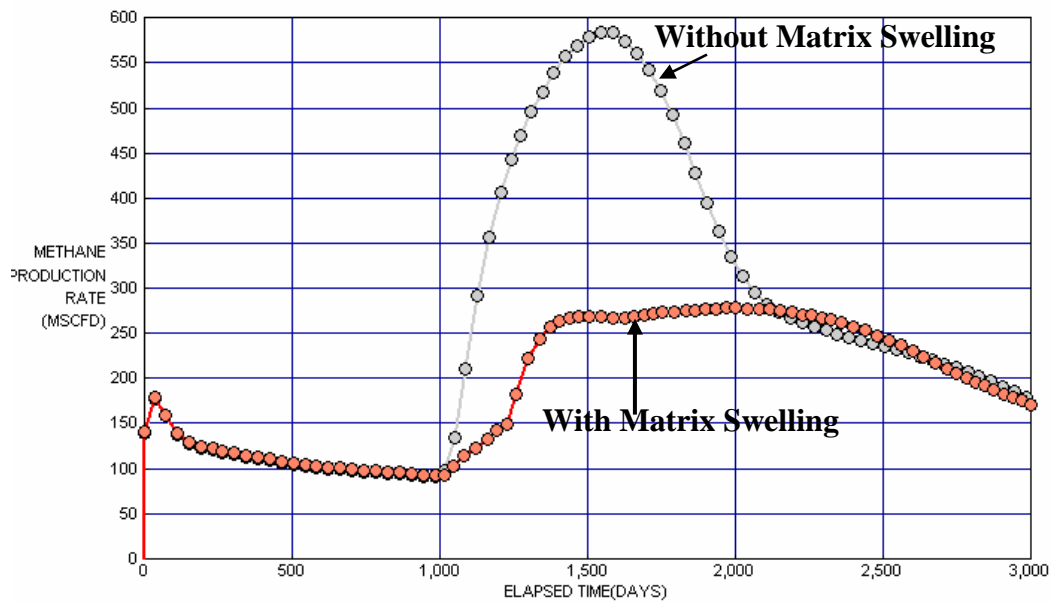
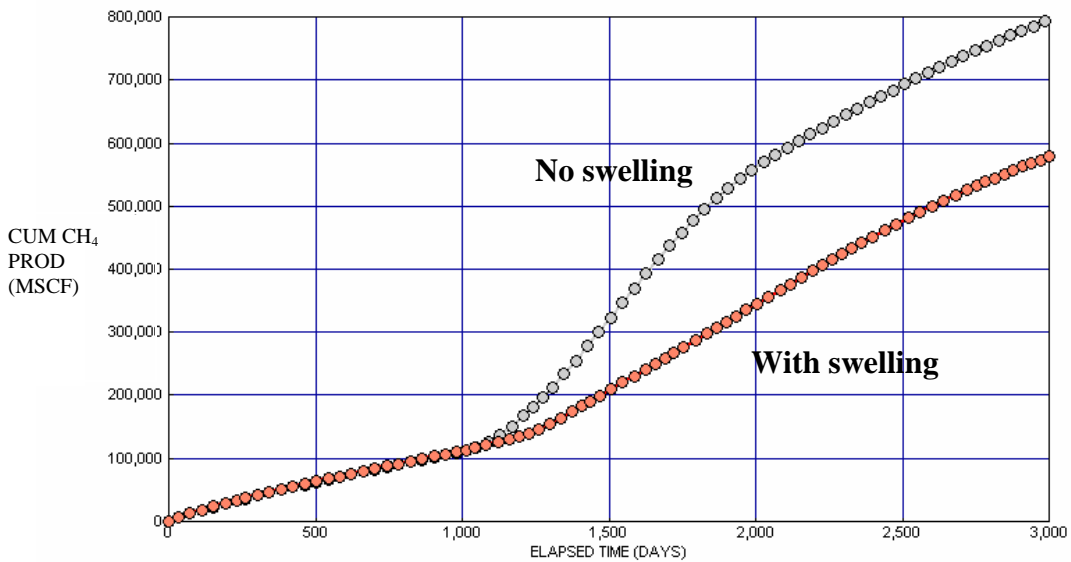Figure 7: Effect of matrix swelling on methane production rate.

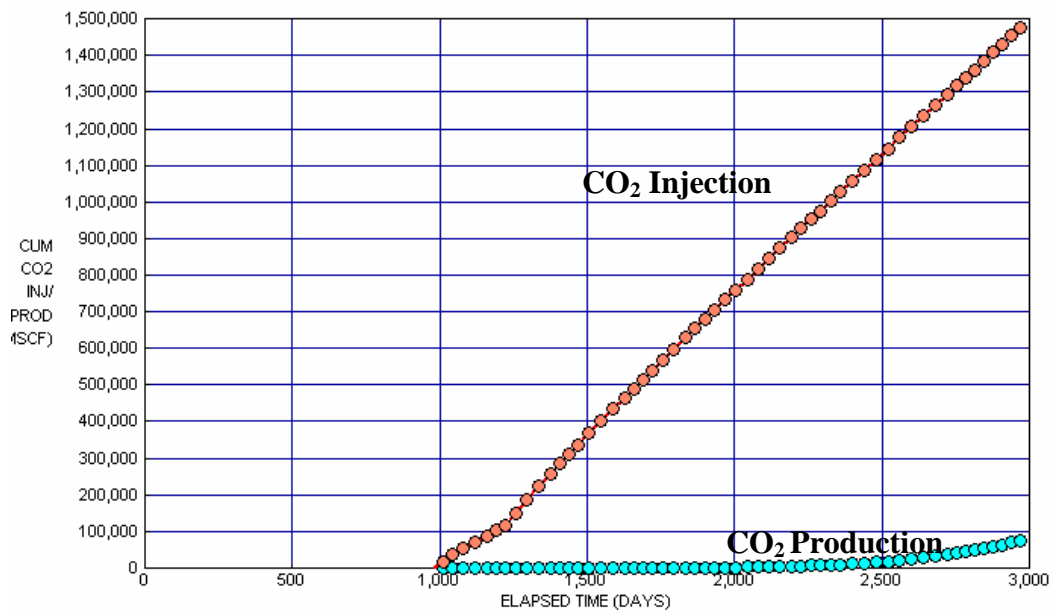Figure 8: Effect of matrix swelling on cumulative production.

Figure 9: Amount of CO_2 injected, produced and sequestered.